

# PAXQuery: Efficient Parallel Processing of Complex XQuery

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**Abstract**—Increasing volumes of data are being produced and exchanged over the Web, in particular in tree-structured formats such as XML or JSON. This leads to a need of highly scalable algorithms and tools for processing such data, capable to take advantage of massively parallel processing platforms.

This work considers the problem of efficiently parallelizing the execution of complex nested data processing, expressed in XQuery. We provide novel algorithms showing how to translate such queries into PACT, a recent framework generalizing MapReduce in particular by supporting many-input tasks. We present the first formal translation of complex XQuery algebraic expressions into PACT plans, and demonstrate experimentally the efficiency and scalability of our approach.

**Index Terms**—XQuery processing, XQuery parallelization, XML data management.

## 1 INTRODUCTION

To scale data processing up to very large data volumes, platforms are increasingly relying on *implicit parallel* frameworks [9], [20], [51]. The main advantage of using such frameworks is that processing is distributed across many sites without the application having to explicitly handle data fragmentation, fragment placement etc.

By far the most widely adopted framework, MapReduce [20] features a very simple processing model consisting of two operations, *Map* which distributes processing over sets of (key, value) pairs, and *Reduce* which processes the sets of results computed by *Map* for each distinct key. However, the simplicity of this processing model makes complex computations hard to express. Therefore, high-level data analytics languages such as Pig [39], Hive [48] or Jaql [12], that are translated (compiled) into MapReduce programs, have emerged. Still, complex processing translates to large and complex MapReduce programs, which may miss parallelization opportunities and thus execute inefficiently.

Recently, more powerful abstractions for implicitly parallel data processing have emerged, such as the *Resilient Distributed Datasets* [51] or *Parallelization Contracts* [9] (**PACT**, in short). In particular, PACT pushes the idea of MapReduce further by (i) manipulating records with any number of fields, instead of (key, value) pairs, (ii) enabling the *definition of custom parallel operators* by means of second-order functions, and (iii) allowing one parallel operator to receive as input the outputs of *several* other such operators. Due to its declarative nature, a PACT program can have multiple physical

execution plans with varying performance. At compile time, the compiler chooses an optimal strategy (plan) that maximizes parallelisation opportunities, and thus efficiency. The PACT model lies at the core of the **Stratosphere** platform [47], which can read data from and write data to the Hadoop Distributed File System (HDFS) [3].

In this work, we are interested in the *implicit parallelization of XQuery* [43], the W3C's standard query language for XML data. The language has been recently enhanced with features geared towards XML analytics [22], such as explicit grouping. Given a very large collection of documents, evaluating an XQuery query that *navigates over these documents and also joins results from different documents* raises performance challenges, which may be addressed by parallelism. In contrast with prior work [13], [19], [29], we are interested in *implicit parallelism*, which does not require the application (or the user) to partition the XML input nor the query across many nodes.

The contributions of this work are the following:

- 1) We present a novel *methodology for massively parallel evaluation of XQuery*, based on PACT and previous research in algebraic XQuery optimization.
- 2) We provide a *translation algorithm* from the algebraic operators required by a large powerful fragment of XQuery into operators of the PACT parallel framework. This enables parallel XQuery evaluation *without requiring data or query partitioning effort from the application*.

Toward this goal, we first map XML data instances into PACT nested records, to ensure XML query results are returned after the PACT manipulations of nested records. Second, we bridge the gap between the XQuery algebra, and in particular, many flavors of joins [21], [34], [35] going beyond simple conjunctive equality joins, and PACT operators which (like MapReduce) are fundamentally designed around the equality of key values in their inputs.

Our translation of complex joins is of interest beyond

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the XQuery context, as it may enable compiling other high-level languages [12], [39], [48] into PACT and other models, and thus, their efficient parallelization by platforms such as Stratosphere [47] or Spark [4].

- 3) We fully implemented our translation technique into our PAXQuery platform. We present experiments demonstrating that our translation approach (i) effectively parallelizes XQuery evaluation taking advantage of the PACT framework, and (ii) scales well beyond alternative approaches for implicitly parallel XQuery evaluation, in particular as soon as joins across documents are present in the workload.

It is worth observing that, thanks to XML flexibility, PAXQuery can be exploited for efficiently processing large amount of heterogeneous data, going from relational to JSON data. While JSON data can be easily and efficiently encoded into XML data in a streaming fashion, well established techniques exist to efficiently map rational data into XML data (e.g., [24], [32]); actually, a basic encoding of tables to flat XML files would suffice, as PAXQuery is able to efficiently perform various kind of joins, in order to recombine data coming from XML documents corresponding to different tables.

The remainder of the paper is organized as follows. Section 2 introduces the problem by means of an example. Section 3 provides background on XML, XQuery, and the PACT model. Section 4 overviews our complete solution and characterizes the XQuery algebras targeted by our translation. Section 5 presents the translation algorithm from XQuery plans to PACT, at the core of this work. Section 6 describes our experimental evaluation. Section 7 discusses related work and then we conclude.

## 2 MOTIVATION

**Example 1.** Consider the following XQuery that extracts the name of users, and the items of their auctions (if any):

```
let $pc := collection('people'),
    $cc := collection('closed_auctions')
for $p in $pc/site/people/person, $i in $p/@id
let $n := $p/name
let $r :=
  for $c in $cc//closed_auction,
    $b in $c/buyer/@person,
    $s in $c/seller/@person
  let $a := $c/itemref
  where $i = $b or $i = $s
  return $a
return <res>{$n,$r}</res>
```

We would like to evaluate this query over two large collections of documents (concerning people, respectively closed auctions) stored in HDFS. Evaluating the query in a massively parallel fashion as previously proposed e.g. in [29] requires the programmer to explicitly insert parallelization primitives in the query, which requires time and advanced expertise. Alternatively, one could partition the XML data, as in [13], [19], and run the query as such. This also requires human input (potentially different for each query); moreover, for complex XQuery queries like the one in Example 1, it also requires manual decomposition of the query into (i) “embarrassingly parallel” subqueries which can be directly run in parallel over many documents, and (ii) a “recomposition” query that applies the remaining query operations.

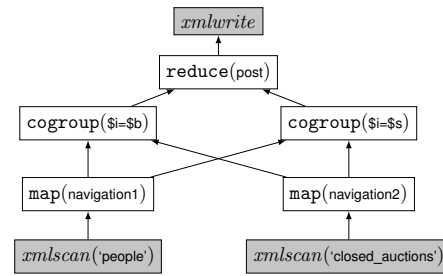


Fig. 1. Outline of the PACT program generated by PAXQuery for the XQuery in Example 1.

In contrast, given this query, PAXQuery generates *in a fully automated fashion* the PACT program shown in Figure 1. We outline here its functioning while on purpose omitting details, which will be introduced later on. The *xmllscan*(‘people’) and *xmllscan*(‘closed\_auctions’) operators scan (in parallel) the respective collections and transform each document into a record. Next, the *map* operators navigate in parallel within the records thus obtained, following the query’s XPath expressions, and bind the query variables. The next operators in the PACT plan (*cogroup*) go beyond MapReduce. In a nutshell, a *cogroup* can be seen as a *reduce* operator on multiple inputs: it groups together records from all inputs sharing the same key value, and then it applies a user-defined function on each group. In this example, the functions are actually quite complex (we explain them in Section 5). The difficulty they have to solve is to correctly express (i) the *disjunction* in the *where* clause of the query, and (ii) the *outerjoin* semantics frequent in XQuery: in this example, a <res> element must be output even for people with no auctions. The output of both *cogroup* operators is received by the *reduce*, which builds join results between people and closed\_auctions, while the last *xmllstore* builds and returns XML results.

This approach enables us to take advantage of the Stratosphere platform [47] in order to automatically parallelize complex XML processing, expressed in a rich dialect of XQuery. In contrast, *state-of-the-art solutions require partitioning, among nodes and by hand, the query and/or the data*. Moreover, using PACT gives PAXQuery a performance advantage over MapReduce-based systems, because PACT’s more expressive massively parallel operators allow more efficient query implementations.

## 3 BACKGROUND

In the following, we provide background on the XML data model and XQuery dialect we target (Section 3.1), and the PACT programming model used by Stratosphere (Section 3.2).

### 3.1 XML and XQuery fragment

**XML data.** We view XML data as a forest of ordered, node-labeled, unranked trees, as outlined by the simple grammar:

$$\begin{aligned} \text{Tree } d &::= s_i \mid l_i[f] \\ \text{Forest } f &::= () \mid f_i f \mid d \end{aligned}$$

A tree  $d$  is either a text node ( $s_i$ ), or an element node having the label  $l_i$  and a forest of children; in accordance with the W3C’s XML data model, each node is endowed with a unique identity, which we materialize through the  $i$  index. A forest  $f$

```

Q1  let $ic := collection('items')
    let $i := $ic/site/regions//item
    return count($i)

Q2  let $ic := collection('items')
    for $i in $ic/site/regions//item
    let $l := $i/location/text()
    group by $l
    return <res><name>{$l}</name>
        <num>{count($i)}</num></res>

Q3  let $pc := collection('people'),
    $cc := collection('closed_auctions')
    for $p in $pc/site/people/person, $i in $p/@id
    let $n := $p/name/text()
    let $a :=
        for $t in $cc/site/closed_auctions/closed_auction,
        $b in $t/buyer/@person
        where $b = $i
        return $t
    return <item person="{ $n }">{count($a)}</item>

```

Fig. 2. Sample queries expressed in our XQuery grammar.

is a sequence of XML trees;  $()$  denotes the empty forest. For the sake of presentation we omitted attributes in our grammar. **XQuery dialect.** We consider a representative subset of the XQuery 3.0 language [43]. Our goal was to cover (i) the main navigating features of XQuery, and (ii) key constructs to express analytical style queries e.g. aggregation, explicit grouping, or rich comparison predicates. However, extensions to support other XQuery constructs e.g. *if* or *switch* expressions, can be integrated into our proposal in a straightforward manner. The full presentation of our XQuery dialect, including the grammar, can be found in Appendix A.

Figure 2 provides three sample queries. A path starts from the root of each document in a *collection* found at URI *Uri*, or from the root of one *document* at URI *Uri*, or from the bindings of a previously introduced *variable*. The path expression dialect *Path* belongs to the XPath<sup>{//,[]}</sup> language [37]. We support two different types of comparators in predicates: (*ValCmp*) to compare atomic values, and (*NodeCmp*) to compare nodes by their identity. Finally, the *group by* clause groups tuples based on variable values.

In Figure 2, queries  $Q_1$  and  $Q_2$  use only one collection of documents while query  $Q_3$  joins two collections. Further,  $Q_2$  and  $Q_3$  construct new XML elements while  $Q_1$  returns the result of an aggregation over nodes from the input documents.

### 3.2 PACT framework

The PACT model [9] is a generalization of MapReduce, based on the concept of parallel data processing operators. PACT plans are DAGs of *implicit parallel operators*, that are optimized and translated into *explicit parallel data flows* by Stratosphere.

We introduce below the PACT data model and formalize the semantics of its operators.

**Data model.** PACT plans manipulate *records* of the form:

$$r = ((f_1, f_2, \dots, f_n), (i_1, i_2, \dots, i_k))$$

where  $1 \leq k \leq n$  and:

- $(f_1, f_2, \dots, f_n)$  is a list of *fields*  $f_i$ . In turn, a field  $f_i$  is either an atomic value (string) or a list  $(r'_1, \dots, r'_m)$  of records.
- $(i_1, i_2, \dots, i_k)$  is a possibly empty list of record positions in  $[1 \dots n]$  indicating the *key* fields for the record. Each of the key fields must be an atomic value.

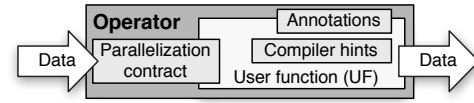


Fig. 3. PACT operator outline.

The *key* of a record  $r$ , denoted by  $r.key$ , is the list of all the key fields  $(f_{i_1}, f_{i_2}, \dots, f_{i_k})$ . We denote by  $r[i]$  the field  $i$  of record  $r$ . A  $\perp$ -record is a record whose fields consist of *null* ( $\perp$ ) values. Finally,  $\mathcal{R}$  denotes the infinite domain of records. **Path indexes** are needed to describe navigation through records. A path index  $pi$  obeys the grammar  $pi := j.pi \mid \epsilon$ , with  $j \geq 0$ . *Navigation through  $r$  along a path index  $j.pi$*  first selects  $r[j]$ . If  $pi$  is empty ( $\epsilon$ ), then we are at the target field. Otherwise, if  $r[j]$  is a list of records (the field at position  $j$  is nested),  $pi$  navigation is performed on each record.

**Data sources and sinks** are, respectively, the starting and terminal nodes of a PACT plan. The input data is stored in files; the function parameterizing data source operators specifies how to structure the data into records. In turn, data is output into files, with the destination and format similarly controlled by an output function.

**Semantics.** Operators are data processing nodes in a PACT plan. Each operator manipulates bags of records; we write  $\{r_1, r_2, \dots, r_n\}$  to indicate a bag of  $n$  records. From now on, for simplicity, we will call a PACT operator simply a PACT, whenever this does not cause confusion. As Figure 3 shows, a PACT consists of (i) a *parallelization contract*, (ii) a *user function* (UF in short) and (iii) optional *annotations* and *compiler hints* characterizing the UF behaviour. We describe these next.

- 1) **Parallelization contract.** A PACT can have  $k \geq 1$  inputs, each of which is a finite bag of records. The contract determines how input records are organized into *groups*.
- 2) **User function.** The UF is executed independently over each bag of records created by the parallelization contract, therefore these executions can take place in parallel. For each input bag of records, the UF returns a bag of records.
- 3) Annotations and/or compiler hints may be used to enable optimizations (with no impact on the semantics), thus we do not discuss them further.

The semantics of the PACT *op* given as input  $k$  bags of records  $I_1, \dots, I_k$ , with  $I_i \subset \mathcal{R}$ ,  $1 \leq i \leq k$ , and having the parallelization contract  $c$  and the user function  $f$  is:

$$op(I_1, \dots, I_k) = \bigcup_{s \in c(I_1, \dots, I_k)} f(s)$$

In the above,  $c$  builds bags of records by grouping the input records belonging to bags  $I_1, \dots, I_k$ ;  $f$  is invoked on each bag produced by  $c$ , and the resulting bags are unioned.

**Predefined contracts.** Although the PACT model allows creating custom parallelization contracts, a set of them for the most common cases is built-in:

- *Map* has a single input, and builds a singleton for each input record. Formally, given the bag  $I_1 \subset \mathcal{R}$  of records, *Map* is defined as:

$$c_{mp}(I_1) = \{\{r\} \mid r \in I_1\}$$



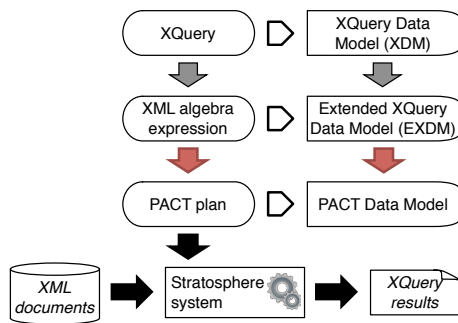


Fig. 4. Translation process overview.

- *Reduce* also has a single input and groups together all records that share the same key. Given a bag of input records  $I_1$ :

$$c_{rd}(I_1) = \{s = \{r_1, r_2, \dots, r_m\} \mid r_1, r_2, \dots, r_m \in I_1 \text{ and } r_1.key = r_2.key = \dots = r_m.key \text{ and } \nexists r' \in I_1 \setminus s \text{ such that } (r'.key = r_1.key)\}$$

- *Cross* builds the cartesian product of two inputs.
- *Match* builds all pairs of records from its two inputs, which share the same key. Thus, given  $I_1, I_2 \subset \mathcal{R}$ :

$$c_{mt}(I_1, I_2) = \{(r_1, r_2) \mid r_1 \in I_1, r_2 \in I_2 \text{ and } r_1.key = r_2.key\}$$

- *CoGroup* can be seen as a “Reduce on two inputs”; it groups the records from the both inputs, sharing the same key value. Formally, given  $I_1, I_2 \subset \mathcal{R}$ :

$$c_{cg}(I_1, I_2) = \{s = \{r_{11}, \dots, r_{1m}, r_{21}, \dots, r_{2j}\} \mid r_{11}, \dots, r_{1m} \in I_1 \text{ and } r_{21}, \dots, r_{2j} \in I_2 \text{ and } \forall r, r' \in s : r.key = r'.key \text{ and } \nexists r'' \in (I_1 \cup I_2) \setminus s \text{ such that } r''.key = r_{11}.key\}$$

## 4 OUTLINE

Our approach for implicit parallel XQuery evaluation is to *translate* XQuery into PACT plans as depicted in Figure 4. The central vertical stack traces the query translation steps from the top to the bottom, while at the right of each step we show the data models manipulated by that step.

First, the XQuery query is represented as an *algebraic expression*, on which multiple optimizations can be applied. XQuery translation into different algebra formalisms and the subsequent optimization of resulting expressions have been extensively studied [10], [15], [42], [52]. In Section 4.1, we characterize the class of XML algebras over which our translation technique can be applied, while we present the nested-tuple data model and algebra used by our work in Section 4.2.

Second, the XQuery logical expression is translated into a PACT plan; we explain this step in detail in Section 5.

Finally, the Stratosphere platform receives the PACT plan, optimizes it, and turns it into a data flow that is evaluated in parallel; these steps are explained in [9].

### 4.1 Assumptions on the XQuery algebra

Numerous logical algebras have been proposed for XQuery [10], [21], [34], [42]. While the language has a functional flavor, most algebras decompose the processing

of a query into *operators*, such as: *navigation* (or *tree pattern matching*), which given a path (or tree pattern) query, extracts from a document *tuples* of nodes matching it; *selection*; *projection*; *join* etc.

A significant source of XQuery complexity comes from *nesting*: an XQuery expression can be nested in almost any position within another. In particular, nested queries challenge the optimizer, as straightforward translation into nested plans leads to very poor performance. For instance, in Figure 2,  $Q_3$  contains a nested subquery for  $\$t \dots \text{return } \$t$  (shown indented in the figure); let us call it  $Q_4$  and write  $Q_3 = e(Q_4)$ . A naïve algebraic expression of such a query would evaluate  $Q_4$  once per result of  $e$  in order to compute  $Q_3$  results, which is typically inefficient.

Efficient optimization techniques translate nested XQuery into *unnested plans relying on joining and grouping* [7], [21], [35]. Thus, a smarter method to represent such query is to connect the sub-plans of  $Q_4$  and  $e$  with a *join* in the plan of  $Q_3$ ; the join condition in this example is  $\$b=\$i$ . Depending on the query shape, such *decorrelating joins* may be *nested* and/or *outer*.

Our goal is to complement existing engines, which translate from XQuery to an internal algebra, by an efficient compilation of this algebra into an implicit parallel framework such as PACT. This enables plugging a highly parallel back-end to an XQuery engine to improve its scalability. Accordingly, we aim to adapt to any XML query algebra satisfying the following two assumptions:

- The algebra is tuple-oriented (potentially using nested tuples).
- The algebra is rich enough to support decorrelated (unnested) plans even for nested XQuery; in particular we consider that the query plan has been unnested before we start translating it into PACT.

Three observations are of order here.

First, to express complex queries without nesting, the algebra may include *any type of joins* (*conjunctive/disjunctive, value or identity-based, possibly nested, possibly outer*), as well as *grouping*; accordingly, we must be able to translate all such operators into PACT.

Second, a tuple-based algebra for XQuery provides *border* operators for (i) creating tuples from XML trees, in leaf operators of the algebraic plan; (ii) constructing XML trees out of tuples, at the top of the algebraic plan, so that XML results can be returned.

Finally, we require no optimization but unnesting [35] to be applied on the XML algebraic plan before translating it to PACT; however, any optimization *may* be applied before (and orthogonal to) our translation.

### 4.2 Algebra and data model

In the sequel, we present our work based on the algebra in [34]. We describe the nested tuple data model manipulated by this algebra, then present its operators.

**Nested tuples data model for XML.** The data model extends the W3C’s XPath/XQuery data model with *nested tuples* to facilitate describing algebraic operations.

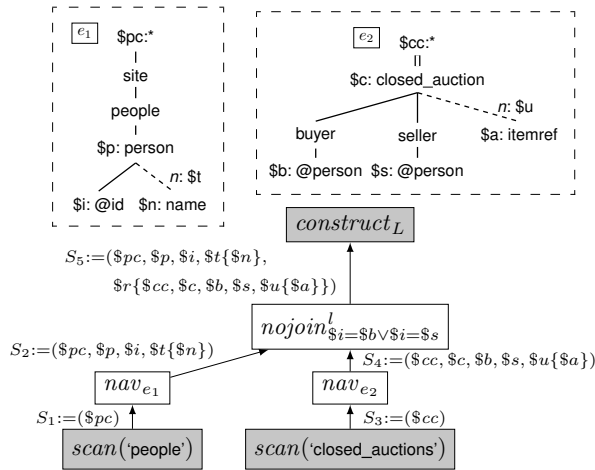


Fig. 5. Sample logical plan for the query in Example 1.

Formally, a tuple  $t$  is a set of *variable-value* pairs:

$$\{(\$V_1, v_1), (\$V_2, v_2), \dots, (\$V_k, v_k)\}$$

where the variable names  $\$V_i$  are all distinct, and each value  $v_i$  is either (i) an *item*, which can be an XML node, atomic value or  $\perp$ , or (ii) an *homogeneous* collection of tuples (see below).

Three flavours of *collections* are considered, namely: *lists*, *bags* and *sets*, denoted as  $(t_1, t_2, \dots, t_n)$ ,  $\{(t_1, t_2, \dots, t_n)\}$ , and  $\{t_1, t_2, \dots, t_n\}$ , respectively.

*Tuple schemas* are needed for our discussion. The schema  $S$  of a tuple  $t$  is a set of pairs  $\{(\$V_1, S_1), \dots, (\$V_n, S_n)\}$  where each  $S_i$  is the schema of the value of the variable  $\$V_i$ . We use *val* to denote the type of (any) atomic value, and *node* to denote an XML node type. Further, a collection of values has the schema  $C\{S\}$  where  $C$  is *list*, *bag*, or *set*, depending on the kind of collection, and  $S$  is the schema of all values in the collection i.e., only *homogeneous* collections are considered.

The tuple resulting from the *concatenation* of the lists of fields of two tuples  $t_1$  and  $t_2$  is denoted by  $t_1 + t_2$ .

**Algebraic representation of XQuery.** In the following, we introduce the translation process and the main operators by example. A methodology for translating our XQuery dialect into the algebra we consider was described in [7], and detailed through examples in [33]. The complete list of algebra operators and their semantics can be found in Appendix B.

**Example 1 (continuation).** The algebraic plan corresponding to the XQuery introduced in Section 2 is shown in Figure 5. For simplicity, we omit the variable types in the operators schema and only show the variable names. We discuss the operators starting from the leaves.

The XML *scan* operators take as input the ‘people’ (respectively ‘closed\_auctions’) XML forests and create a tuple out of each tree in them. XML scan is one of the *border* operators.

XPath and XQuery may perform *navigation*, which, in a nutshell, *binds variables to the result of path traversals*. Navigation is commonly represented through *tree patterns*, whose nodes carry the labels appearing in the paths, and where some *target nodes* are also annotated with names of variables to be bound, e.g.  $\$pc$ ,  $\$i$  etc. The algebra we

consider allows to *consolidate as many navigation operations from the same query as possible within a single navigation tree pattern*, and in particular *navigation performed outside of the for clauses* [7], [21], [36]. Large navigation patterns lead to more efficient query execution, since patterns can be matched very efficiently against XML documents; for instance, if the pattern only uses *child* and *descendant* edges, it can be matched in a single pass over the input [17]. In the spirit of *generalized tree patterns* [18], *annotated tree patterns* [40], or *XML access modules* [6], we assume a navigation (*nav*) operator parameterized by an *extended tree pattern* (ETP) supporting multiple returning nodes, child and descendant axis, and nested and optional edges.

Consider the ETP  $e_1$  in Figure 5. The node labeled  $\$n:name$  is (i) *optional* and (ii) *nested* with respect to its parent node  $\$p:person$ , since by XQuery semantics: (i) if a given  $\$p$  lacks a name, it will still contribute to the query result; (ii) if a given  $\$p$  has several names, *let* binds them all into a single node collection. The operator  $nav_{e_1}$  concatenates each input tuple successively with all *@id* attributes (variable  $\$i$ ) and *name* elements (variable  $\$n$ ) resulting from the embeddings of  $e_1$  in the value bound to  $\$pc$ . Observe that variable  $\$n$  is *nested* into variable  $\$t$ , which did not appear in the original query; in fact,  $\$t$  is created by the XQuery to algebra translation to hold the nested collection with values bound to  $\$n$ . The operator  $nav_{e_2}$  is generated in a similar fashion. Therefore, in the previous query, ETPs  $e_1$  and  $e_2$  correspond to the following fragment:

```
for $p in $pc/site/people/person, $i in $p/@id
let $n := $p/name
let $r :=
  for $c in $cc//closed_auction,
  $b in $c/buyer/@person,
  $s in $c/seller/@person
  let $a := $c/itemref
```

Above the *nav* operators in Figure 5, we find a nested join ( $nojoin^l$ ) on a disjunctive predicate  $\rho$ , which selects those people that appear as buyers *or* sellers in an auction.

Finally, the XML construction ( $construct_L$ ) is the *border* operator responsible for transforming a collection of tuples to XML forests [25], [46]. The information on how to build the XML forest is specified by a list  $L$  of *construction tree patterns* (CTPs in short), attached to the *construct* operator. For each tuple in its input,  $construct_L$  builds one XML tree for each CTP in  $L$  [34]. In our example,  $L$  contains a single CTP that generates for each tuple an XML tree consisting of elements of the form  $\langle res \rangle \{ \$n, \$r \} \langle /res \rangle$ . We omit further details here; the interested reader may find them in Appendix B.  $\diamond$

**Full operator set.** We briefly comment below on the rest of operators that are handled by our translation.

The rest of unary operators are very close to their known counterparts in nested relational algebra. These are *flatten* ( $flat_p$ ) which unnests tuples, *selection* ( $sel_p$ ) based on a predicate  $\rho$ , *projection* ( $proj_v$ ), *aggregation* ( $agg_{p,a,\$r}$ ) computing the usual aggregates over (nested) records, and value-based *duplicate elimination* ( $dupelim_v$ ). One operator that is slightly different is group-by ( $grp_{G_{id}, G_v, \$r}$ ). In order to conform to

$\frac{v_i \rightarrow r_i \quad i = 1 \dots n}{((\$V_1, v_1), \dots, (\$V_n, v_n)) \rightarrow r_1 + \dots + r_n}$	(TUPLE)
$\frac{v :: \text{node}}{v \rightarrow (id(v), v)}$	(XMLNODE)
$\frac{v :: \text{val}}{v \rightarrow (v)}$	(ATOMICVALUE)
$\frac{v :: C\{S\} \quad v \equiv [t_1, t_2, \dots, t_m] \quad t_i \rightarrow r_i \quad i = 1 \dots m}{v \rightarrow ((r_1, \dots, r_m))}$	(COLLVALUE)

Fig. 6. Data model translation rules.

XML semantics, the operator may group by identity based on the variables in  $G_{id}$ , and/or by value on the variables in  $G_v$  [21], [34].

Binary operators include the usual cartesian product (*prod*), join (*join<sub>ρ</sub>*), outer join (*ojoin<sub>ρ</sub>*) and nested outer join (*nojoin<sub>ρ</sub>*).

## 5 XML ALGEBRA TO PACT

Within the global approach depicted in Figure 4, this section describes our contribution: translating (i) from the Extended XQuery Data Model (or EXDM, in short) into the PACT Data Model (Section 5.1) and (ii) from algebraic expressions into PACT plans (Section 5.2). The most complex technical issues are raised by the latter.

XQuery algebraic plans are translated into PACT plans recursively, operator by operator; for each XQuery operator, the translation outputs one or several PACT operators for which we need to choose (i) the *parallelization contract* (and possibly its corresponding *key fields*), and (ii) the *user function*, which together determine the PACT behavior. The hardest to translate are those algebraic operators whose input *cannot* be fragmented based on conjunctive key equalities (e.g., disjunctive joins). This is because all massively parallel operators in PACT are based on key equality comparisons [9].

**Translation rules.** As in [42], we use deduction rules to specify our translation. In a nutshell, a deduction rule describes *how the translation is performed when some conditions are met over the input*. Our rules rely on *translation judgments*, noted as  $J, J_i$ , and are of the form:

$$\frac{\text{cond } J_1 \dots J_n}{J}$$

stating that the translation  $J$  (conclusion) is recursively made in terms of translations  $J_1 \dots J_n$  (premises) when the (optional) condition *cond* holds. The translation judgments  $J_i$  are optional; their absence denotes that the rule handles the “fixpoint” (start of the recursive translation).

### 5.1 Translating XML tuples into PACT records

Rules for translating instances of EXDM into those of PACT rely on translation judgments of the form  $\boxed{t \rightarrow r}$ , or: “the EXDM instance  $t$  translates into the PACT record  $r$ ”.

The translation rules appear in Figure 6, where  $+$  denotes record concatenation. *Rules produce records whose key fields*

TABLE 1  
Auxiliary functions details.

Signature	Description
$S; V \mapsto_{id} F$	Given the variable paths $V$ bound to XML nodes according to $S$ , returns the index path positions $F$ in $S$ -records corresponding to the XML node IDs.
$S; V \mapsto_v F$	Given a list of variable paths $V$ bound to XML nodes, atomic values or collections, according to $S$ , returns the index path positions $F$ of the values of those variables in $S$ -records.
$S; V \mapsto_{id,v} F$	“Union” of the two previous functions.
$S; L \mapsto L'$	Given a list of CTPs $L$ , returns the CTPs $L'$ where variables are replaced with corresponding fields in $S$ -records.
$S; e \mapsto e'$	Given an ETP $e$ whose root is a variable in $S$ , builds a new ETP $e'$ rooted with the corresponding field position in $S$ -records.
$S; \rho \mapsto \rho'$	As above (replace ETPs with predicates).
$S_1, S_2; \rho \mapsto \rho'$	Given a predicate $\rho$ referencing variables in tuples in $S_1$ and $S_2$ , generates a new predicate $\rho'$ referencing field positions in $S_1$ - and $S_2$ -records.

are not set yet; as we will see in Section 5.2, the keys are filled in by the translation.

Rule (TUPLE) produces a record from a tuple: it translates each tuple value, and then builds the output record  $r$  by concatenating the results according to tuple order.

There are three rules that can be triggered by rule (TUPLE). First, rule (XMLNODE) translates an XML node into a record with two fields: the first one contains the XML ID, while the second is the text serialization of the XML tree rooted at the node. In turn, rule (ATOMICVALUE) translates an XML value. Finally, rule (COLLVALUE) translates a tuple collection into a single-field record that contains the nested collection of records corresponding to the tuples in the input.

### 5.2 Translating algebraic expressions to PACT

Rules for translating an algebraic expression into a PACT plan are based on judgments of the form  $\boxed{A \Rightarrow P}$ , or: “ $A$  translates into a PACT plan  $P$ ”. All rules are defined recursively over the structure of their input  $A$ ; for instance, the translation of  $A = sel_\rho(A')$  relies on the PACT plan  $P'$  resulting from the translation of the smaller expression  $A'$ , and so on.

The specific behavior of each rule is encoded in the choice of the parallelization contracts (and corresponding keys) and the user functions, so this is what we comment on below.

**Preliminaries.** In the translation, we denote a PACT operator by its parallelization contract  $c$ , user function  $f$  and the list  $K$  of key field positions in the PACT input. In particular:

- a unary PACT is of the form  $c_f^K$ ; if  $K = \emptyset$ , for simplicity we omit it and use just  $c_f$ .
- a binary PACT is of the form  $c_f^{K_1, K_2}$ , assuming that the key of the left input records consists of the fields  $K_1$  and that of the right input records of  $K_2$ , respectively.

To keep track of attribute position through the translation, we use a set of *helper functions* associating to variables

$$\frac{\mathcal{A} \Rightarrow \mathcal{P} \quad S_A; L \mapsto L'}{\text{construct}_L(\mathcal{A}) \Rightarrow \text{xmlwrite}_{L'}(\mathcal{P})} \quad (\text{CONSTRUCTION})$$

$$\frac{}{\text{scan}(f) \Rightarrow \text{xmlscan}(f)} \quad (\text{SCAN})$$

Fig. 7. Border operators translation rules.

$$\frac{\mathcal{A} \Rightarrow \mathcal{P} \quad S_A; e \mapsto e' \quad f := \overline{\text{nav}}(e')}{\text{nav}_e(\mathcal{A}) \Rightarrow \text{mp}_f(\mathcal{P})} \quad (\text{NAVIGATION})$$

$$\frac{\begin{array}{c} \mathcal{A} \Rightarrow \mathcal{P} \\ S_A; G_{id} \mapsto_{id} G'_{id} \quad S_A; G_v \mapsto_v G'_v \\ K := G'_{id} + G'_v \quad f := \overline{\text{grp}}(K) \end{array}}{\text{grp}_{G_{id}, G_v, \$r}(\mathcal{A}) \Rightarrow \text{rd}_f^K(\mathcal{P})} \quad (\text{GROUP-BY})$$

$$\frac{\mathcal{A} \Rightarrow \mathcal{P} \quad S_A; p \mapsto_v pi \quad f := \overline{\text{flat}}(pi)}{\text{flat}_p(\mathcal{A}) \Rightarrow \text{mp}_f(\mathcal{P})} \quad (\text{FLATTEN})$$

$$\frac{\mathcal{A} \Rightarrow \mathcal{P} \quad S_A; \rho \mapsto \rho' \quad f := \overline{\text{sel}}(\rho')}{\text{sel}_\rho(\mathcal{A}) \Rightarrow \text{mp}_f(\mathcal{P})} \quad (\text{SELECTION})$$

$$\frac{\mathcal{A} \Rightarrow \mathcal{P} \quad S_A; V \mapsto_{id,v} V' \quad f := \overline{\text{proj}}(V')}{\text{proj}_V(\mathcal{A}) \Rightarrow \text{mp}_f(\mathcal{P})} \quad (\text{PROJECTION})$$

$$\frac{\begin{array}{c} \mathcal{A} \Rightarrow \mathcal{P} \quad S_A; p \mapsto_v pi \\ \text{if } p.\text{length} \neq 1 \\ \text{then } f := \overline{\text{agg}}_n(pi, a) \quad U := \text{mp}_f \\ \text{else } K := \emptyset \quad f := \overline{\text{agg}}(pi, a) \quad U := \text{rd}_f^K \end{array}}{\text{agg}_{p,a,\$r}(\mathcal{A}) \Rightarrow U(\mathcal{P})} \quad (\text{AGGREGATION})$$

$$\frac{\mathcal{A} \Rightarrow \mathcal{P} \quad S_A; V \mapsto_v K \quad f := \overline{\text{dupelim}}}{\text{dupelim}_V(\mathcal{A}) \Rightarrow \text{rd}_f^K(\mathcal{P})} \quad (\text{DUPELIM})$$

Fig. 8. Unary operators translation rules.

from  $S$ , the index positions of the corresponding fields in the PACT records. These functions are outlined in Table 1; we use the term  $S$ -records as a shortcut for records obtained by translating tuples that conform to schema  $S$ . The helper functions implementation details are quite straightforward.

### 5.2.1 Border operators translation

Figure 7 outlines the translation of border operators.

Rule (CONSTRUCTION) translates the logical  $\text{construct}_L$  operator into a data sink that uses our output function  $\text{xmlwrite}$ . For each input record from  $\mathcal{P}$ ,  $\text{xmlwrite}$  generates XML content using the list of construction patterns in  $L'$  and writes the results to a file.

Rule (SCAN) translates the logical operator  $\text{scan}_f$  into a data source built up by means of our input function  $\text{xmlscan}$ . For each XML document in  $f$ ,  $\text{xmlscan}$  returns a single-field record holding the content of the document.

### 5.2.2 Unary operators translation

Unary operators are translated by the rules in Figure 8.

Rule (NAVIGATION) uses an auxiliary judgment that translates the input ETP  $e$  into  $e'$  using  $S_A$ . Navigation is applied over each record independently, and thus we use a PACT with a  $\text{Map}$  contract. The UF is  $\overline{\text{nav}}$ , which generates new records

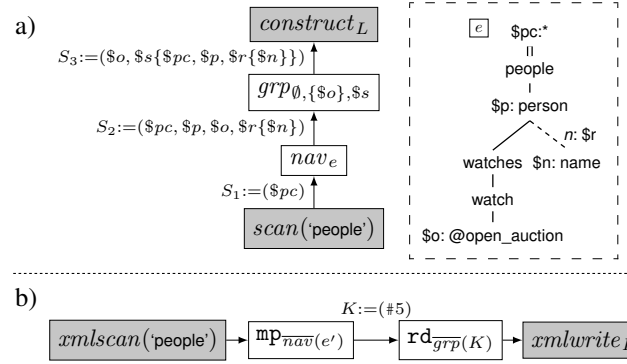


Fig. 9. Logical expression (a) and corresponding PACT plan (b) for the query in Example 2.

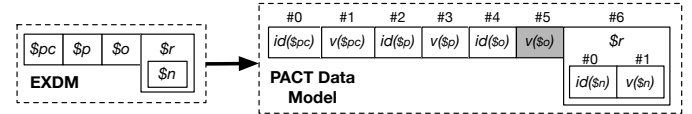


Fig. 10. Example of tuple representation in PACT.

from the (possibly partial) embeddings of  $e'$  in each input record.

Rule (GROUP-BY) translates a group-by expression into a PACT with a  $\text{Reduce}$  contract, as the records need to be partitioned by the value of their grouping fields. The fields in  $K$ , which form the key used by the  $\text{Reduce}$  contract, are obtained appending  $G'_v$  to  $G'_{id}$ .  $K$  is also handed to the  $\overline{\text{grp}}$  UF, which creates one record from each input collection of records. The new record contains the values for each field in  $K$ , and a new field which is the collection of the input records themselves.

**Example 2.** The following XQuery groups together the people that share interest in the same auctions:

```
let $pc := collection('people')
for $p in $pc//people/person,
    $o in $p/watches/watch/@open_auction
let $n := $p/name
group by $o
return <res><a>{$o}</a>{$n}</res>
```

The XML algebraic expression generated from this query is shown in Figure 9a. Using the judgments in Figure 8, the expression is translated into the PACT plan of Figure 9b. Observe that the grouping variable  $\$o$  is translated into field position #5, since: *i*) two record fields are created for each of the first variables  $\$pc$  and  $\$p$  (rules (TUPLE) and (XMLNODE) in Figure 6) and *ii*) the subsequent two fields correspond to the id-value pair for  $\$o$ ; the mapping of  $S_2$  tuples into PACT records is shown in Figure 10 (the key field is highlighted). The same holds for the encoding of fields used in other figures.  $\diamond$

Rule (FLATTEN) translates a flatten expression into a  $\text{Map}$  PACT, that applies the flattening UF  $\overline{\text{flat}}$  on each input record independently. The path  $pi$  to the nested collection is obtained from  $p$  using  $S_A$ .

Rule (SELECTION) produces a  $\text{Map}$  PACT that applies the selection to each record produced by  $\mathcal{P}$ . Selection is performed by the  $\text{sel}$  UF, which uses the filtering condition  $\rho'$  obtained from  $\rho$  and  $S_A$ .



$\frac{\mathcal{A}_1 \Rightarrow \mathcal{P}_1 \quad \mathcal{A}_2 \Rightarrow \mathcal{P}_2 \quad f := \overline{concat}}{prod(\mathcal{A}_1, \mathcal{A}_2) \Rightarrow \mathbf{cr}_f(\mathcal{P}_1, \mathcal{P}_2)}$			(CARTESIANPRODUCT)
$\frac{\mathcal{A}_1 \Rightarrow \mathcal{P}_1 \quad \mathcal{A}_2 \Rightarrow \mathcal{P}_2 \quad S_{\mathcal{A}_1}, S_{\mathcal{A}_2}; \rho \mapsto \rho' \quad \rho' \rightarrow_l K_1 \quad \rho' \rightarrow_r K_2 \quad f := \overline{concat}}{join_\rho(\mathcal{A}_1, \mathcal{A}_2) \Rightarrow \mathbf{mt}_f^{K_1, K_2}(\mathcal{P}_1, \mathcal{P}_2)}$			( $\wedge$ JOIN $_{=}$ )
$\frac{\mathcal{A}_1 \Rightarrow \mathcal{P}_1 \quad \mathcal{A}_2 \Rightarrow \mathcal{P}_2 \quad S_{\mathcal{A}_1}, S_{\mathcal{A}_2}; \rho \mapsto \rho' \quad \rho' \rightarrow_l K_1 \quad \rho' \rightarrow_r K_2 \quad f := \overline{oconcat_l}}{ojoin_\rho^l(\mathcal{A}_1, \mathcal{A}_2) \Rightarrow \mathbf{cg}_f^{K_1, K_2}(\mathcal{P}_1, \mathcal{P}_2)}$			(LO $\wedge$ JOIN $_{=}$ )
$\frac{\mathcal{A}_1 \Rightarrow \mathcal{P}_1 \quad \mathcal{A}_2 \Rightarrow \mathcal{P}_2 \quad S_{\mathcal{A}_1}, S_{\mathcal{A}_2}; \rho \mapsto \rho' \quad \rho' \rightarrow_l K_1 \quad \rho' \rightarrow_r K_2 \quad f := \overline{noconcat_l}}{nojoin_\rho^l(\mathcal{A}_1, \mathcal{A}_2) \Rightarrow \mathbf{cg}_f^{K_1, K_2}(\mathcal{P}_1, \mathcal{P}_2)}$			(NLO $\wedge$ JOIN $_{=}$ )

Fig. 11. Cartesian product and conjunctive equi-join translation rules.

Rule (PROJECTION) translates a projection expression into a PACT using a *Map* contract. The positions  $V'$  of the fields that should be kept by the projection are obtained from  $V$  using the schema  $S_A$ .

The translation of (AGGREGATION) is interesting as it can use one PACT or another, depending on the path  $p$  to the variable being aggregated. If the variable is contained in a nested collection, i.e.,  $p.length \neq 1$ , we produce a PACT with a *Map* contract; for each input record, the  $\overline{agg}_n$  UF executes the aggregation operation  $a$  over the field pointed by  $pi$  and outputs a record with the aggregation results.

Otherwise, if the aggregation is executed on the complete input collection, we use a *Reduce* contract wrapping the input in a single group. The  $\overline{agg}$  UF creates an output record having (i) a field with a nested collection of all input records and (ii) a field with the result of executing the aggregation  $a$  over the field pointed by  $pi$ .

Finally, rule (DUPELIM) translates a duplicate elimination expression into a PACT with a *Reduce* contract. Each group handed to the UF holds the bag of records containing the same values in the fields pointed by  $K$ ; the duplicate elimination UF, denoted by  $\overline{dupelim}$ , outputs only one record from the group.

### 5.2.3 Binary operators translation

The rules are depicted in Figure 11; we assume that the inputs  $\mathcal{A}_1$  and  $\mathcal{A}_2$  of the algebraic binary operator translate into the PACT plans  $\mathcal{P}_1$  and  $\mathcal{P}_2$ .

**a) Cartesian product.** This operator requires the simple *concatenation* UF, taking as input a pair of records, and outputting their concatenation:  $\overline{concat}(r_1, r_2) = r_1 + r_2$ .

Rule (CARTESIANPRODUCT) translates a cartesian product into a *Cross* PACT with a  $\overline{concat}$  UF.

**b) Joins with conjunctive equality predicates.** This family comprises joins on equality predicates, which can be simple (natural) equi-joins, or outer joins (without loss of generality we focus on left outer joins).

**b.1) Conjunctive equi-join.** The conjunctive equi-join operator is translated by rule ( $\wedge$  JOIN $_{=}$ ), as follows. First, the predicate  $\rho$  over  $\mathcal{A}_1$  and  $\mathcal{A}_2$  translates into a predicate  $\rho'$  over records produced by  $\mathcal{P}_1$  and  $\mathcal{P}_2$ . Then, the list of fields

pointed by the left ( $\rightarrow_l$ ), resp. right ( $\rightarrow_r$ ) of the condition  $\rho'$  are extracted, and finally they are used as the keys of the generated *Match* PACT.

**b.2) Left outer conjunctive equi-join.** In the rule (LO  $\wedge$  JOIN $_{=}$ ), the output PACT is a *CoGroup* whose keys are taken from the fields of the translated join predicate  $\rho'$ . The *CoGroup* contract groups the records produced by  $\mathcal{P}_1$  and  $\mathcal{P}_2$  sharing the same key. Then, the  $\overline{oconcat_l}$  UF that we describe next is applied over each group, to produce the expected result.

**Definition 1** ( $\overline{oconcat_l}$ ): The left outer concatenation UF,  $\overline{oconcat_l}$ , of two record bags  $\{\{r_1, \dots, r_x\}\}$  and  $\{\{r'_1, \dots, r'_y\}\}$  is defined as:

- If  $y \neq 0$ , the cartesian product of the two bags.
- Otherwise,  $\{\{r_1 + \perp', \dots, r_x + \perp'\}\}$  i.e., concatenate each left input record with a  $\perp$ -record having the schema (structure) of the right records.  $\diamond$

**b.3) Nested left outer conjunctive equi-join.** Similar to the non-nested case, rule (NLO  $\wedge$  JOIN $_{=}$ ) translates the nested left outer conjunctive equi-join into a *CoGroup* PACT whose key is extracted from  $\rho'$ . However, we need a different UF in order to generate the desired right-hand side nested records, and we define it below.

**Definition 2** ( $\overline{noconcat_l}$ ): The nested left outer concatenation UF,  $\overline{noconcat_l}$ , of the bags  $\{\{r_1, \dots, r_x\}\}$  and  $\{\{r'_1, \dots, r'_y\}\}$  is defined as:

- If  $y \neq 0$ ,  $\{\{r_1 + (r'_1, \dots, r'_y), \dots, r_x + (r'_1, \dots, r'_y)\}\}$  i.e., nest the right set as a new field concatenated to each record from the left.
- Otherwise,  $\{\{r_1 + (\perp'), \dots, r_x + (\perp')\}\}$  i.e., add to each left record a field with a list containing a  $\perp$ -record conforming to the schema of the right records.  $\diamond$

**Example 3.** The following XQuery extracts the name of users and the items that they bought (if any):

```
let $pc := collection('people'),
    $cc := collection('closed_auctions')
for $p in $pc/site/people/person, $i in $p/@id
let $n := $p/name
let $r :=
  for $c in $cc//closed_auction,
    $b in $c/buyer/@person
  let $a := $c/itemref
  where $i = $b
  return $a
return <res>{$n, $r}</res>
```

The query translates into the algebraic expression depicted in Figure 12a, while the corresponding PACT plan is shown in Figure 12b.

Rule (NLO  $\wedge$  JOIN $_{=}$ ) translates the nested left outer conjunctive equi-join into a PACT with a *CoGroup* contract that groups together all records having the same values in the fields corresponding to  $\$i$  ( $K_1$ ) and  $\$b$  ( $K_2$ ), and applies our  $\overline{noconcat_l}$  UF on them.  $\diamond$

**c) Joins with disjunctive equality predicates.** Translating joins with disjunctive equality predicates is harder. The reason is that PACT contracts are centered around *equality* of record fields, and thus *inherently not suited* to disjunctive semantics. To solve this mismatch, our translation relies on using more



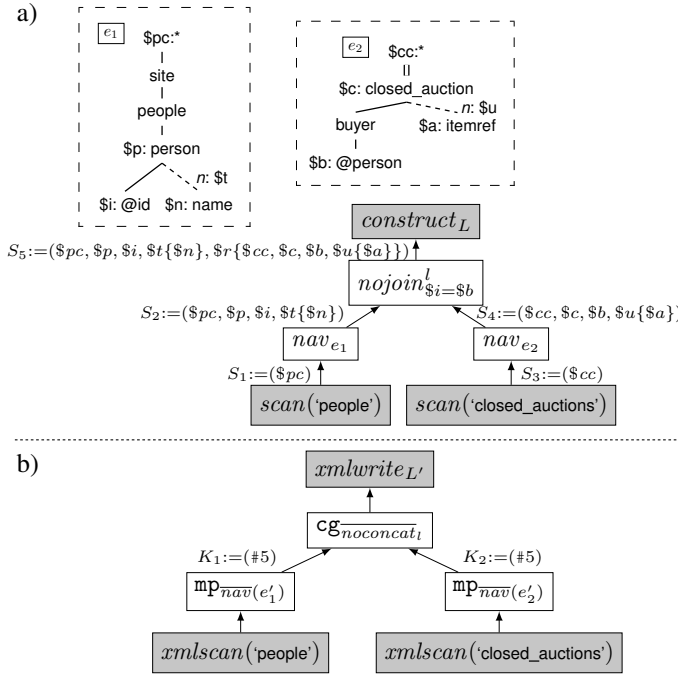


Fig. 12. Logical expression (a) and corresponding PACT plan (b) for the query in Example 3.

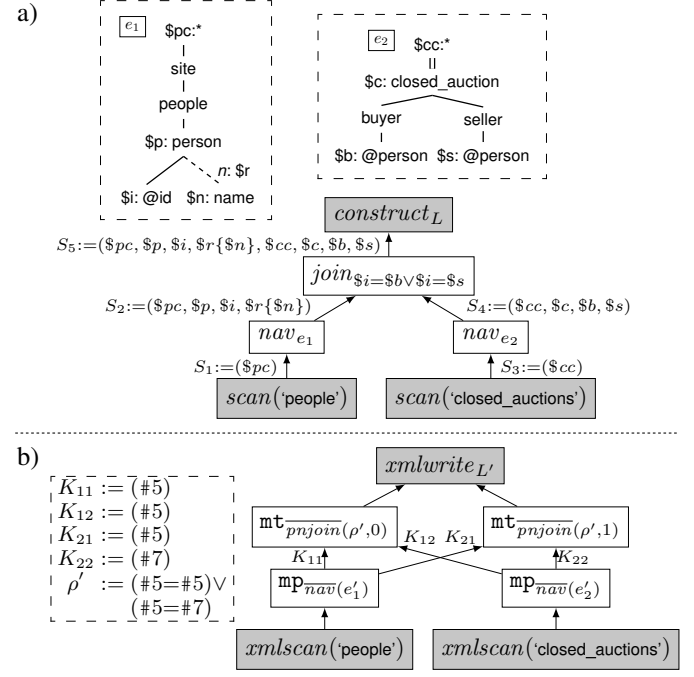


Fig. 14. Logical expression (a) and corresponding PACT plan (b) for the query in Example 4.

$$\begin{array}{c}
 \frac{
 \begin{array}{c}
 \mathcal{A}_1 \Rightarrow \mathcal{P}_1 \quad \mathcal{A}_2 \Rightarrow \mathcal{P}_2 \\
 S_{A_1}, S_{A_2}; \rho \mapsto \rho' \quad \rho' \equiv \rho'_1 \vee \dots \vee \rho'_n \\
 \rho'_k \rightarrow_l K_{1k} \quad \rho'_k \rightarrow_r K_{2k} \\
 f_k := \overline{pnjoin}(\rho', k-1) \quad k = 1 \dots n \\
 U := \{\text{mt}_{f_1}^{K_{11}, K_{21}}, \dots, \text{mt}_{f_n}^{K_{1n}, K_{2n}}\}
 \end{array}
 }{
 join_\rho(\mathcal{A}_1, \mathcal{A}_2) \Rightarrow U(\mathcal{P}_1, \mathcal{P}_2)
 } \quad (\vee JOIN_=)
 \\
 \\
 \frac{
 \begin{array}{c}
 \mathcal{A}_1 \Rightarrow \mathcal{P}_1 \quad \mathcal{A}_2 \Rightarrow \mathcal{P}_2 \\
 S_{A_1}, S_{A_2}; \rho \mapsto \rho' \quad \rho' \equiv \rho'_1 \vee \dots \vee \rho'_n \\
 \rho'_k \rightarrow_l K_{1k} \quad \rho'_k \rightarrow_r K_{2k} \\
 f_k := \overline{nopnjoin}_l(\rho', k-1) \quad k = 1 \dots n \\
 U := \{\text{cg}_{f_1}^{K_{11}, K_{21}}, \dots, \text{cg}_{f_n}^{K_{1n}, K_{2n}}\} \\
 S_{A_1} \rightsquigarrow K \quad f' := \text{opost}_{l \vee}
 \end{array}
 }{
 ojoin_\rho^l(\mathcal{A}_1, \mathcal{A}_2) \Rightarrow \text{rd}_{f'}^K(U(\mathcal{P}_1, \mathcal{P}_2))
 } \quad (\text{LO } \vee JOIN_=)
 \\
 \\
 \frac{
 \begin{array}{c}
 \mathcal{A}_1 \Rightarrow \mathcal{P}_1 \quad \mathcal{A}_2 \Rightarrow \mathcal{P}_2 \\
 S_{A_1}, S_{A_2}; \rho \mapsto \rho' \quad \rho' \equiv \rho'_1 \vee \dots \vee \rho'_n \\
 \rho'_k \rightarrow_l K_{1k} \quad \rho'_k \rightarrow_r K_{2k} \\
 f_k := \overline{nopnjoin}_l(\rho', k-1) \quad k = 1 \dots n \\
 U := \{\text{cg}_{f_1}^{K_{11}, K_{21}}, \dots, \text{cg}_{f_n}^{K_{1n}, K_{2n}}\} \\
 S_{A_1} \rightsquigarrow K \quad f' := \text{nopost}_{l \vee}
 \end{array}
 }{
 nojoin_\rho^l(\mathcal{A}_1, \mathcal{A}_2) \Rightarrow \text{rd}_{f'}^K(U(\mathcal{P}_1, \mathcal{P}_2))
 } \quad (\text{NLO } \vee JOIN_=)
 \end{array}$$

Fig. 13. Disjunctive equi-join translation rules.

than one PACT for each operator, as we explain below. The rules are depicted in Figure 13

**c.1) Disjunctive equi-join.** In rule  $(\vee JOIN_=)$ , the predicate  $\rho'$  is generated from  $\rho$  using  $S_{A_1}$  and  $S_{A_2}$ . Then, for each conjunctive predicate  $\rho'_k$  in  $\rho'$ , we create a *Match* whose keys are the fields participating in  $\rho'_k$ . Observe that the UFs of these *Match* operators should guarantee that no erroneous duplicates are generated when the evaluation of more than one conjunctive predicates  $\rho'_i, \rho'_j, i \neq j$  is true for a certain

record. To that purpose, we define the new UF  $\overline{pnjoin}$  below, parameterized by  $k$  and performing a partial negative join.

**Definition 3 ( $\overline{pnjoin}$ ):** Let  $\rho' = \rho'_1 \vee \rho'_2 \vee \dots \vee \rho'_n$  and  $k$  be an integer, with  $0 \leq k < n$ . Given two records  $r_1, r_2$ , the  $\overline{pnjoin}(\rho', k)$  UF evaluates  $\rho'_1 \vee \rho'_2 \vee \dots \vee \rho'_k$  over  $r_1, r_2$ , and outputs  $r_1 + r_2$  if they evaluate to false.  $\diamond$

Note that the UF ensures correct multiplicity of each record in the result.

**Example 4.** The following XQuery extracts the names of users involved in at least one auction, either as buyers or sellers:

```

let $pc := collection('people'),
    $cc := collection('closed_auctions')
for $p in $pc/site/people/person, $i in $p/@id,
    $c in $cc//closed_auction,
    $b in $c/buyer/@person,
    $s in $c/seller/@person
let $n := $p/name
where $i = $b or $i = $s
return <res>{$n}</res>

```

Figure 14a shows the equivalent algebraic expression, while the corresponding PACT plan is shown in Figure 14b.

Rule  $(\vee JOIN_=)$  translates the disjunctive equi-join into two PACTs with *Match* contracts, one per disjunction. Observe that two distinct values (0 and 1) of  $k$  are used in the  $\overline{pnjoin}$  UFs to prevent spurious duplicates, one for the predicate  $\$i = \$b$  and one for  $\$i = \$s$ .  $\diamond$

**c.2) (Nested) left outer disjunctive equi-join.** The translation of the plain and nested variants of the outer disjunctive equi-join, described by the  $(\text{LO } \vee JOIN_=)$  and  $(\text{NLO } \vee JOIN_=)$  rules respectively, are very similar; as illustrated next, the main difference resides in the different post-processing operations they adopt. The translation of these two operators is chal-

lenging because we want to ensure parallel evaluation of each conjunctive join predicate in the disjunction, and at the same time we need to:

- 1) *Avoid the generation of duplicate records.* We adopt a non trivial variation of the technique used previously for disjunctive equi-join.
- 2) *Recognise records generated by the left hand-side expression which do not join any record coming from the right-hand side expression.* We use the XML node identifiers in each left hand-side record to identify it uniquely, so that, after the parallel evaluation of each conjunction, a Reduce post-processing PACT groups all resulting combinations having the same left hand-side record; if none of such combinations exists, the left hand-side record representing a group is concatenated to a (nested)  $\perp$ -record conforming to the right input schema, and the resulting record is output; otherwise the output record(s) are generated from the combinations.

In the first step, we must evaluate in parallel the joins related to predicates  $\rho'_i$ . A PACT with a *CoGroup* contract is built for each conjunctive predicate  $\rho'_k$ . Each such PACT groups together all records that share the same value in the fields pointed by  $\rho'_k$ , then applies the  $\overline{nopnjoin}_l$  UF (see below) on each group, with the goal of avoiding erroneous duplicates in the result; the UF is more complex than  $\overline{pnjoin}$  though, as it has to handle the disjunction and the nesting.  $\overline{nopnjoin}_l$  is parameterized by  $k$ , as we will use it once for each conjunction  $\rho'_k$ . Furthermore,  $\overline{nopnjoin}_l$  takes as input two bags of records and is defined as follows, along the lines of  $\overline{pnjoin}$ .

**Definition 4** ( $\overline{nopnjoin}_l$ ): Let  $\rho' = \rho'_1 \vee \rho'_2 \vee \dots \vee \rho'_n$  be a predicate where each  $\rho'_i$  is conjunctive. Given two input bags  $\{\{r_1, \dots, r_x\}\}$  and  $\{\{r'_1, \dots, r'_y\}\}$ , the  $\overline{nopnjoin}_l(\rho', k)$  UF is defined as follows:

- If the second input is empty ( $y = 0$ ), return  $\{\{r_1 + (\perp'), \dots, r_x + (\perp')\}\}$  i.e., concatenate every left input record with a field containing a nested list of one  $\perp$ -record conforming to the schema of the right input.
- Otherwise, for each left input record  $r_i$ :
  - 1) create an empty list  $c_i$ ;
  - 2) for each  $r'_{j, 1 \leq j \leq y}$ , evaluate  $\rho'_1 \vee \rho'_2 \vee \dots \vee \rho'_k$  over  $r_i$  and  $r'_j$ , and add  $r'_j$  to  $c_i$  if the result is false;
  - 3) if  $c_i$  is empty, then insert into  $c_i$  a  $\perp$ -record with the schema of the right input;
  - 4) output  $r_i$  concatenated with a new field whose value is  $c_i$ .  $\diamond$

The second PACT produced by the  $(LO \vee JOIN=)$  and  $(NLO \vee JOIN=)$  rules uses a *Reduce* contract, taking as input the outputs of all the *CoGroup* operators; its key consists of the XML node identifiers in each left hand-side record (we denote by  $\rightsquigarrow$  the extraction of these fields from the schema). This amounts to grouping together the records originated from the same left input record.

Depending on the join flavor though, this last PACT uses a different UF. For the plain (non-nested) join  $(LO \vee JOIN=)$ , we use the  $\overline{opost}_{l\vee}$  UF producing records with an unnested right side. For the nested join  $(NLO \vee JOIN=)$ , on the other

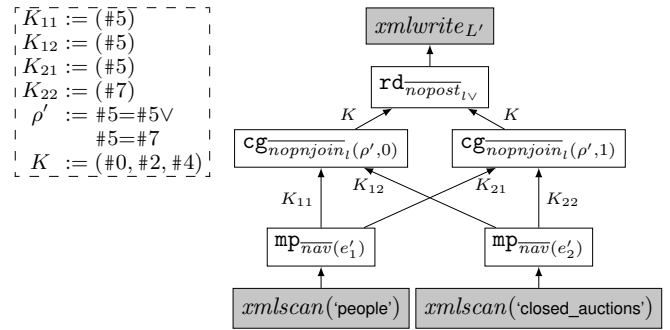


Fig. 15. PACT plan corresponding to the logical expression in Figure 5.

hand, the  $\overline{nopost}_{l\vee}$  UF is used to produce nested records. Due to space constraints, we omit the definition of these UFs here and delegate their details to Appendix C.

**Example 1 (continuation).** Our algorithms translate the algebraic expression shown in Figure 5 into the PACT plan depicted in Figure 15; observe that it is the same PACT plan that was shown in less detail in Figure 1.

Rule  $(NLO \vee JOIN=)$  translates the nested left outer disjunctive equi-join into (i) two PACTs with *CoGroup* contracts, one for each disjunction, and (ii) a PACT with a *Reduce* contract that groups together records originating from the same left-hand side record, i.e.,  $K$  holds field positions #0, #2, #4, which contain the XML node identifiers of  $\$pc, \$p, \$i$ , respectively.  $\diamond$

**d) Joins on inequalities.** Our XQuery subset also supports joins with inequality conditions. In this case, the translation uses *Cross* contracts. Further, just like for joins with disjunctive predicates, the non-nested and nested outer variants of the  $\theta$ -join require more than one PACT. The corresponding translation rules can be found in Appendix D.

**Syntactically complex translation vs. performance** Clearly, complex joins such as those considered in c) could be translated into a single *Cross* PACT over the pairs of records as in d). However, this would be less efficient and scale poorly (number of comparisons quadratic in the input size), as our experiments will demonstrate.

## 6 EXPERIMENTAL EVALUATION

We implemented our PAXQuery translation approach in Java 1.6, and relied on the Stratosphere platform [47] supporting PACT. We first describe the experimental setup, and then present our results.

**Experimental setup.** The experiments run in a cluster of 8 nodes on an 1GB Ethernet. Each node has  $2 \times 2.93\text{GHz}$  Quad Core Xeon CPUs, 16GB RAM and two 600GB SATA hard disks and runs Linux CentOS 6.4. PAXQuery is built on top of Stratosphere 0.2.1; it stores the XML data in HDFS 1.1.2. The reported results are averaged over three runs.

**XML data.** We used XMark [45] data; to study queries joining several documents, we used the `split` option of the XMark generator to create four collections of XML documents, each containing a specific type of XMark subtrees: *users* (10% of

TABLE 2  
Query details.

Query	Collections	Algebra operators (#)	Parallelization contracts (#)
$q_1 - q_3$	<i>users</i>	Navigation (1)	Map (1)
$q_4, q_5$	<i>closed auct.</i>	Navigation (1)	Map (1)
$q_6$	<i>users</i>	Navigation (1)	Map (1)
$q_7$	<i>closed auct.</i>	Navigation (1) Aggregation (2)	Map (2) Reduce (1)
$q_8$	<i>items</i>	Navigation (1) Aggregation (2)	Map (2) Reduce (1)
$q_9$	<i>users</i> <i>closed auct.</i>	Navigation (2) Projection (1) Group-by/aggregation (1) Conj. equi-join (1)	Map (3) Reduce (1) Match (1)
$q_{10}$	<i>users</i> <i>items</i> <i>closed auct.</i>	Navigation (3) Projection (2) NLO conj. equi-join (2)	Map (5) CoGroup (2)
$q_{11}$	<i>users</i>	Navigation (2) Projection (1) Dup. elim. (1) NLO conj. equi-join (1)	Map (3) Reduce (1) CoGroup (1)
$q_{12}$	<i>users</i> <i>closed auct.</i>	Navigation (2) Projection (1) NLO conj. equi-join/ aggregation (1)	Map (3) CoGroup (1)
$q_{13}$	<i>users</i> <i>closed auct.</i>	Navigation (2) Projection (1) NLO disj. equi-join (1)	Map (3) Reduce (2) CoGroup (2)
$q_{14}$	<i>users</i> <i>open auct.</i>	Navigation (2) Projection (1) NLO $\theta$ -join (1)	Map (3) Reduce (2) Cross (1)

the dataset size), *items* (50%), *open auctions* (25%) and *closed auctions* (15%).

All documents are simply stored in HDFS (which replicates them three times), that is, *we do not control the distribution/location of documents over the nodes*.

**XML queries.** We used a subset of XMark queries from our XQuery fragment, and added queries with features supported by our dialect but absent from the original XMark, e.g. joins on disjunctive predicates; all queries are detailed in Appendix E.

Table 2 outlines the queries: the collection(s) that each query carries over, the corresponding algebraic operators and their numbers of occurrences, and the parallelization contracts used in the plan generated by our translation framework. *Queries  $q_9$ - $q_{14}$  all involve value joins, which carry over thousands of documents arbitrarily distributed across the HDFS nodes.*

## 6.1 PAXQuery scalability

Our first goal is to check that PAXQuery brings to XQuery evaluation the desired benefits of implicit parallelism. For this, we fixed a set of queries, generated 11,000 documents (34GB) per node, and varied the number of nodes from 1 to 2, 4, 8 respectively; the total dataset size increases accordingly in a linear fashion, up to 272GB.

Figure 16 shows the response times for each query. Queries  $q_1$ - $q_6$  navigate in the input document according to a given navigation pattern of 5 to 14 nodes; each translates into a *Map* PACT, thus their response time follows the size of

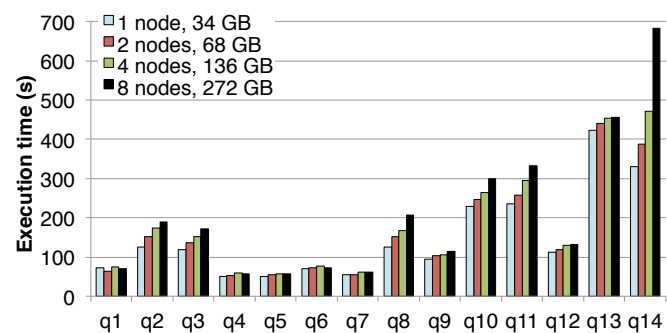


Fig. 16. PAXQuery scalability evaluation.

the input. These queries scale up well; we see a moderate overhead in Figure 16 as the data volume and number of nodes increases.

Queries  $q_7$  and  $q_8$  apply an aggregation over all the records generated by a navigation. For both queries, the navigation generates nested records and the aggregation consists on two steps. The first step goes over the nested fields in each input record, and thus it uses a *Map* contract. The second step is executed over the results of the first. Therefore, a *Reduce* contract that groups together all records coming from the previous operator is used. Since the running time is dominated by the **Map** PACTs which parallelize very well,  $q_7$  and  $q_8$  also scale up well.

Queries  $q_9$ - $q_{12}$  involve conjunctive equi-joins over the collections. Query  $q_{13}$  executes a NLO disjunctive equi-join, while  $q_{14}$  applies a NLO  $\theta$ -join. We notice a very good scaleup for  $q_9$ - $q_{13}$ , whose joins are translated in many PACTs (recall the rules in Figure 13). In contrast,  $q_{14}$ , which translates into a *Cross* PACT, scales noticeably less well. *This validates the interest of translating disjunctive equi-joins into many PACTs (as our rules do), rather than into a single Cross*, since, despite parallelization, it fundamentally does not scale.

## 6.2 Comparison against other processors

To evaluate the performance of our processor against existing alternatives, we started by comparing it *on a single node* with other popular centralized XQuery processors. The purpose is to validate our choice of an XML algebra as outlined in Section 4.2 as input to our translation, by demonstrating that *single-site* query evaluation based on such an algebra is efficient. For this, we compare our processor with BaseX 7.7 [8], Saxon-PE 9.4 [44] and Qizx/open 4.1 [41], on a dataset of 11000 XML documents (34GB).

Table 3 shows the response times for each query and processor; the shortest time is shown in bold, while **OOM** stands for *out of memory*, and **TO** for *timeout* (above 2 hours). In Table 3, we identify two query groups. First,  $q_1$ - $q_8$  do not feature joins; while the performance varies across systems, only BaseX and PAXQuery are able to run all these queries. PAXQuery outperforms other systems because, compiled in PACT, it is able to exploit the multicore architecture.

In the second group, queries  $q_9$ - $q_{14}$  join across the documents. None of the competing XQuery processors completes their evaluation, while PAXQuery executes them quite fast. For these, the usage of outer joins and multicore parallelization are key to this good performance behavior.

TABLE 3  
Query evaluation time (1 node, 34GB).

Query	Evaluation time (seconds)			
	BaseX	Saxon-PE	Qizx/open	PAXQuery
$q_1$	206	145	90	<b>72</b>
$q_2$	629	OOM	OOM	<b>125</b>
$q_3$	600	OOM	OOM	<b>120</b>
$q_4$	189	OOM	84	<b>51</b>
$q_5$	183	125	183	<b>51</b>
$q_6$	233	162	109	<b>70</b>
$q_7$	181	111	88	<b>54</b>
$q_8$	599	OOM	OOM	<b>126</b>
$q_9$	TO	OOM	OOM	<b>94</b>
$q_{10}$	OOM	OOM	OOM	<b>229</b>
$q_{11}$	TO	TO	TO	<b>236</b>
$q_{12}$	TO	OOM	OOM	<b>113</b>
$q_{13}$	TO	OOM	OOM	<b>424</b>
$q_{14}$	OOM	OOM	OOM	<b>331</b>

We next compare our system with other *alternatives for implicitly parallel evaluation of XQuery*. As explained in the Introduction, no comparable system is available yet. Therefore, for our comparison, we picked the BaseX centralized system (the best performing in the experiment above) and used Hadoop-MapReduce on one hand, and Stratosphere-PACT on the other hand, to parallelize its execution.

We compare PAXQuery, relying on the XML algebra-to-PACT translation we described, with the following alternative architecture. We deployed BaseX on each node, and parallelized XQuery execution as follows:

- 1) Manually decompose each query into a set of leaf subqueries performing just tree pattern navigation, followed by a recomposition subquery which applies (possibly nested, outer) joins over the results of the leaf subqueries;
- 2) Parallelize the evaluation of the leaf subqueries through one Map over all the documents, followed by one Reduce to union all the results. Moreover, if the recomposition query is not empty, start a new MapReduce job running the recomposition XQuery query over all the results thus obtained, in order to compute complete query results.

This alternative architecture is in-between ChuQL [29], where the query writer *explicitly* controls the choice of Map and Reduce keys, i.e., MapReduce is *visible at the query level*, and PAXQuery where parallelism is completely hidden. In this architecture,  $q_1$ - $q_8$  translate to one Map and one Reduce, whereas  $q_9$ - $q_{14}$  feature joins which translates into a recomposition query and thus a second job.

Table 4 shows the response times when running the query on the 8 nodes and 272GB; the shortest time is in bold. First, we notice that BaseX runs 2 to 5 times faster on Stratosphere than on Hadoop. This is due to Hadoop's checkpoints (writing intermediary results to disk) while Stratosphere currently does not, trading reliability for speed. For queries without joins ( $q_1$ - $q_8$ ), PAXQuery is faster for most queries than BaseX on Hadoop or Stratosphere; this simply points out that our in-house tree pattern matching operator (physical implementation of *nav*) is more efficient than the one of BaseX. Queries with

TABLE 4  
Query evaluation time (8 nodes, 272GB).

Query	Evaluation time (seconds)		
	BaseX Hadoop-MR	BaseX Stratosphere-PACT	PAXQuery
$q_1$	465	<b>66</b>	70
$q_2$	773	282	<b>189</b>
$q_3$	762	243	<b>172</b>
$q_4$	244	72	<b>58</b>
$q_5$	237	72	<b>57</b>
$q_6$	488	<b>70</b>	73
$q_7$	245	74	<b>62</b>
$q_8$	576	237	<b>206</b>
$q_9$	OOM	OOM	<b>114</b>
$q_{10}$	OOM	OOM	<b>299</b>
$q_{11}$	OOM	OOM	<b>334</b>
$q_{12}$	OOM	OOM	<b>132</b>
$q_{13}$	OOM	OOM	<b>456</b>
$q_{14}$	OOM	OOM	<b>683</b>

joins ( $q_9$ - $q_{14}$ ) fail in the competitor architecture again. The reason is that intermediary join results grow too large and this leads to an out-of-memory error. PAXQuery evaluates such queries well, based on its massively parallel (outer) joins.

### 6.3 Conclusions of the experiments

Our experiments demonstrate the efficiency of an XQuery processor built on top of PACT.

First, our scalability evaluation has shown that the translation to PACT allows PAXQuery to parallelize every query execution step with no effort required to partition, redistribute data etc., and thus to scale out with the number of machines in a cluster. The only case where scale-up was not so good is  $q_{14}$  where we used a *Cross* (cartesian product) to translate an inequality join; an orthogonal optimization here would be to use a smarter dedicated join operator for such predicates, e.g. [38].

Second, we have shown that PAXQuery outperforms competitor XQuery processors, whether centralized or distributed over Hadoop and Stratosphere. None of the competing processors was able to evaluate any of our queries with joins across documents on the data volumes we considered, highlighting the need for efficient parallel platforms for evaluating such queries.

## 7 RELATED WORK

**Massively parallel XML query processing.** In this area, MRQL [23] proposes a simple SQL-like XML query language implemented through a few operators directly compilable into MapReduce. Like our XQuery fragment, MRQL queries may be nested, however, its dialect does not allow expressing the rich join flavours that we use. Further, the XML navigation supported by MRQL is limited to XPath, in contrast to our richer navigation based on tree patterns with multiple returning nodes, and nested and optional edges.

ChuQL [29] is an XQuery extension that exposes the MapReduce framework to the developer in order to distribute computations among XQuery engines; this leaves the parallelization work to the programmer, in contrast with our implicit



itly parallel approach which does not expose the underlying parallelism at the query level.

HadoopXML [19] and the recent [13] process XML queries in Hadoop clusters by *explicitly fragmenting the input data* in a schema-driven, respectively, query-driven way, which is effective when querying one single huge document. In contrast, we focus on the frequent situation when no single document is too large for one node, but there are many documents whose global size is high, and queries may both *navigate and join* over them. Further, we do not require any partitioning work from the application level.

After the wide acceptance of Hadoop, other parallel execution engines and programming abstractions conceived to run custom data intensive tasks over large data sets have been proposed: PACT [9], Dryad [27], Hyracks [16] or Spark [51]. Among these, the only effort at parallelizing XQuery is the ongoing VXQuery project [5], translating XQuery into the Algebricks algebra, which compiles into parallel plans executable by Hyracks. In contrast, PAXQuery translates into an implicit parallel logical model such as PACT. Thus, our algorithms do not need to address underlying parallelization issues such as data redistribution between computation steps etc. which [16] explicitly mentions.

XQuery processing in centralized settings has been thoroughly studied, in particular through algebras in [21], [34], [35], [42]. In this work, our focus is on *extending the benefits of implicit large-scale parallelism to a complex XML algebra*, by formalizing its translation into the implicitly parallel PACT paradigm. As shown by our experiments, even on top of the Hadoop/Stratosphere-based architectures used in the experimental comparison with PAXQuery, existing XML processors [8], [41], [44] cannot scale in the presence of joins across multiple documents of large collections. Our algebraic based approach, instead, allows to delegate much more to Stratosphere system wrt the distributed solution proposed in Section 6, where joins remain internal to the XQuery engine.

XML data management has also been studied from many other angles, e.g. on top of column stores [15], distributed with [30] or without [1] an explicit fragmentation specification, in P2P [31] etc. We focus on XQuery evaluation through the massively parallel PACT framework, which leads to specific translation difficulties we addressed.

**Parallelizable nested languages.** Recently, many high-level languages which translate into massively parallel frameworks have been proposed; some of them work with nested data and/or feature nesting in the language, thus somehow resemble XQuery. While PAXQuery's implementation is specific to XQuery, the concepts shown in this work are applicable to these other languages.

Jaql [12] is a scripting language tailored to JSON data, which translates into MapReduce programs; Meteor [26], also for JSON, translates into PACT. None of these languages handles XQuery semantics exactly, since JSON does not feature node identity; the languages are also more limited, e.g. Jaql only supports equi-joins.

The Asterix Query Language [11], or AQL in short, is based on FLOWR expressions and resembles XQuery, but ignores node identity which is important in XQuery and which we

support. Like VXQuery, AQL queries are translated into Algebricks; recall that unlike our translation, its compilation to the underlying Hyracks engine needs to deal with parallelization related issues.

Finally, other higher level languages that support nested data models and translate into parallel processing paradigms include Pig [39] or Hive [48]. Our XQuery fragment is more expressive, in particular supporting more types of joins. In addition, Pig only allows two levels of nesting in queries, which is a limitation. In contrast, we translate XQuery into unnested algebraic plans with (possibly nested, possibly outer) joins and grouping which we parallelize, leading to efficient execution even for (originally) nested queries.

**Complex operations using implicit parallel models.** The problem of evaluating complex operations through implicit parallelism is of independent interest. For instance, the execution of join operations using MapReduce has been studied extensively. Shortly after the first formal proposal to compute equi-joins on MapReduce [50], other studies extending it [14], [28] or focusing on the processing of specific join types such as multi-way joins [2], set-similarity joins [49], or  $\theta$ -joins [38], appeared. PAXQuery is the first to translate a large family of joins (which can be used outside XQuery), into the more flexible PACT parallel framework.

## 8 CONCLUSION AND FUTURE WORK

We have presented the PAXQuery approach for the implicit parallelization of XQuery, through the translation of an XQuery algebraic plan into a PACT parallel plan. We targeted a rich subset of XQuery 3.0 including recent additions such as explicit grouping, and demonstrated the efficiency and scalability of PAXQuery with experiments on collections of hundreds of GBs.

For future work, we contemplate the integration of indexing techniques into PAXQuery to improve query evaluation time. Further, we would like to explore reutilization of intermediary results in the PACT framework to enable efficient multiple-query processing.

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